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14. ABSTRACT
Major accomplishments
Theory:
-Developed a theory of fault-tolerant quantum dynamical decoupling (DD).
-Showed how to construct optimized DD procedures from empirical data.
-Gave conditions for optimal decoherence free subspaces (DFS)
-Developed an optimal algorithm for quantum process tomography, with quadratic speedup over all previously known such algorithms (no connection to Grover speedup).
-Developed a completely positive post-Markovianquantum master equation
-Developed a range of hybrid quantum error correction, DFS, and DD protocols, tailored to various quantum computing

15. SUBJECT TERMS

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Final Report
AFOSR (DARPA) Grant No. F49620-01-1-0468

Principal Investigators:
Daniel Lidar and Aephraim Steinberg

Original objectives

To develop theoretical and experimental techniques for tailoring and optimizing quantum error correction to real-world systems, taking into account experimental limitations and imperfect *a priori* knowledge of sources of error.

To apply theoretical results to an ideal model system, entangled photons, and subsequently to the complex, real-world situation of ultracold atoms trapped in an optical lattice.

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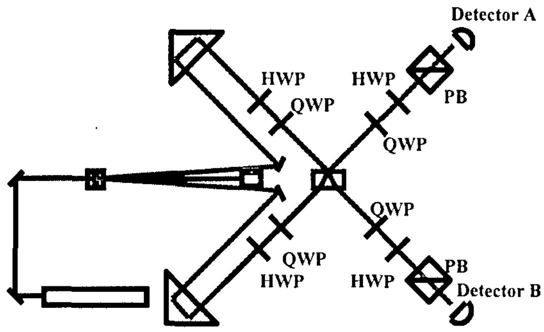
Original scientific goals

Theory:

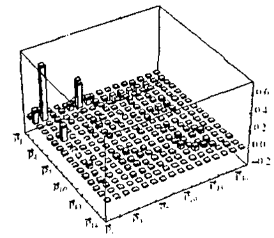
- Dynamical Decoupling (DD): (1) Develop DD theory based on superoperator characterization of decoherence. (2) Optimized and fault-tolerant version of DD.
- Open Quantum Systems: Derive a completely positive **post**-Markovian master equation.
    - Quantum Process Tomography (QPT): Optimized reconstruction of superoperator from sampled and possibly partial data.
    - Develop a general theory of quantum error correction (QEC) that takes into account restricted error model, minimizes qubit resources, and incorporates experimental constraints. Variational optimization of QEC.

Experiment:

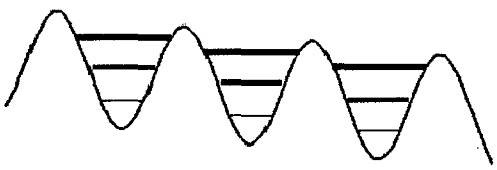
- Develop quantum process tomography for 1- and 2-photon states.
- Perform tailored QEC on correlated photons.
- Extend encoding and tomography to states of >2 photons.
- Develop techniques for quantum state engineering of vibrational motion of atoms in optical lattices.
- Transfer QPT techniques to the atomic system and use to characterize decoherence
- Study applicability of dynamical decoupling approach to optical lattice.



Two-photon tomography



Quantum process tomogram
of Bell-state filter



Ramped vertical lattice for preparation
and
state tomography of ultracold atoms

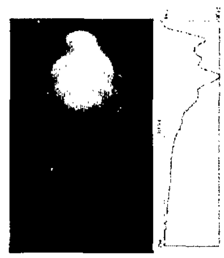


Image of falling atoms
resolving 4 quantum states

Major acccomplishments

Theory:

- Developed a theory of fault-tolerant quantum dynamical decoupling (DD).
- Showed how to construct optimized DD procedures from empirical data.
- Gave conditions for optimal decoherence free subspaces (DFS)
- Developed an optimal algorithm for quantum process tomography, with quadratic speedup over all previously known such algorithms (no connection to Grover speedup).
- Developed a completely positive post-Markovian quantum master equation
- Developed a range of hybrid quantum error correction, DFS, and DD protocols, tailored to various quantum computing implementations, especially solid state spin-based ones.

Experiment:

• First demonstration of QPT on a 2-photon process (Bell-state filter), and discovery of potential error in common construction, along with prescription for correcting it.
• First applications of DFSs in the execution of quantum algorithms (both in photonic and NMR).
• Generation of a 3-photon maximally path-entangled "noon" state, and development of new theory for the complete quantum characterisation of such multi-photon systems in single-mode fiber; demonstration of this theory on a 2-photon version.
• Developed new techniques for preparing quantum states of atomic vibration in an optical lattice.
• Measured density matrices, Wigner & Husimi distributions, and superoperators for atoms in optical lattice under various operations. Observed decoherence due to tunneling, transverse motion, and inhomogeneous broadening.
• Applied pulse echoes to preserving atomic coherence in the lattice. Studied DD approach of multiple pulses in the context of imperfect individual pulses. Compared a variety of pulse shapes and demonstrated that complex pulses could reduce leakage errors.

Original approach proposed – theoretical

The following is a complete list of theoretical objectives given (in the same order) in the original proposal, in the section entitled "Roadmap and Constructive Plan for Accomplishment of Technical Goals".

Measuring the Superoperator

- Devise a method to reconstruct the χ-matrix with optimal fidelity from sampled data.
- Devise a method to reconstruct the Lindblad coefficient matrix from a time-independent quantum process tomography experiment.
- Derive a completely positive post-Markovian master equation.
- Find general conditions for when a small set of parameters suffices to describe a superoperator.
- Devise a quantum process tomography procedure with partial inputs.

Implementation of Quantum Error Correction Schemes

- Develop a general theory of QECC that takes into account restricted error models and minimizes qubit resources.
- Investigate the feasibility of dynamical decoupling using pulses of finite duration.

- Develop a dynamical decoupling theory based on superoperator, rather than Hamiltonian, characterization of decoherence.

- Develop and implement an algorithm for variational optimization of quantum error-correction conditions while accounting for physically available resources.

Original approach proposed – experimental

We proposed to carry out the experimental part of our program using two very different physical systems: entangled photons from a down-conversion source, and neutral atoms trapped in an optical lattice. Entangled photons form an ideal test system for quantum information processing, and afford one the flexibility to study a variety of degrees of freedom and to control the types of errors which are introduced in each degree of freedom, including the ability to vary the level of correlation between different errors. Trapped atoms are considered by many a more promising system for scalable quantum computation (and at the time of this proposal, before the efficient linear-optical quantum computation schemes had appeared, seemed even more so by comparison), and were to provide the acid test for our proposal, as many sources of error and decoherence exist in those systems and no single model will reproduce them all accurately. Furthermore, the potentials any given experimental realization can produce are limited in range, forcing the error-correction strategy to take into account physical constraints. We proposed to use an iterative technique of experimentally estimating the superoperator and modifying the error-correcting codes to achieve an optimal solution for a system when there are multiple sources of error whose physical origin may or may not be precisely known beforehand, and to determine how well such errors can practically be corrected in a system with real experimental constraints.

As a first stage, we proposed to develop a quantum-state tomography system for correlated photon pairs and for single photons. This would be followed up by two-photon quantum process tomography, one of the "trophies" on the quantum information science roadmap, and by studies of effective decoherence introduced using absorbers, partial polarizers, and birefringent media. We proposed to adapt error-correction to the measured superoperators.

The photon experiments would be followed by work on atoms trapped in optical lattices. We proposed to use our abilities to control the phase and amplitude of an optical lattice in real time to carry out quantum state engineering and quantum state & process tomography, which would allow us to study the various sources of decoherence in the lattice. Even without an *a priori* error model, we argued that from the superoperator we would be able to develop optimized error-correction protocols, and proposed to do so in an iterative fashion, concentrating initially on dynamical decoupling approaches.

Milestones – theory

Year 1&2: Dynamical Decoupling Theory -- Develop a dynamical decoupling theory based on superoperator characterization of decoherence.

- Accomplished. A paper giving a complete algorithm for this problem was published: *Phys. Rev. A* **67**, 012324 (2003).
- **Year 1&2: Quantum Process Tomography Theory** -- Develop a method for reconstructing Kraus chi-matrix from sampled data; Develop a method for reconstructing Lindblad a-matrix from time-independent data; Devise a QPT procedure with partial inputs. Accomplished in late '05. The outcome is a method that far exceeded our original expectations: we found an algorithm that provides a quadratic speedup for this problem (unrelated to Grover) relative to all previously known such algorithms: quant-ph/06010343&4.

Year 1&2: Open Quantum Systems Theory -- Derive a completely positive post-Markovian master equation.

- • Accomplished. A paper presenting such a master equation was published in '05: *Phys. Rev. A* **71**, 020101(R) (2005). This immediately attracted attention from the open quantum system community, and already has been the subject of follow-up papers by others.**Year 3&4: Quantum Error Correction with Constraints** -- Develop a general theory of quantum error correction that takes into account restricted error model, minimizes qubit resources, and incorporates experimental constraints.• Accomplished: This turned out to be the major focus area of our research under this grant. 34 published papers were written on this subject during the grant period (including 4 conference proceedings). Our activities covered simplification of design constraints in solid state QC (incl. quantum dots and superconducting qubits), hybrid quantum error correction and prevention methods, QEC tailored to trapped ion and to spin-qubit systems, creation and stabilization of DFSs, and a fault-tolerant protocol for dynamical decoupling. The common thread in this work was to tailor decoherence-management protocols to specific systems likely to be important in the development of quantum computers.**Year 4&5: Iterative Quantum Error Correction** -- Develop a closed-loop algorithm for (variational) optimization of quantum error correction conditions while accounting for physically available resources. The closed-loop part of this milestone is still work in progress (partly in collaboration with Robert Kosut). We did however provide an optimal characterization of DFSs in *Phys. Rev. A* **70**, 012315 (2004).

Milestones – experiment

Year 2: prepare and measure quantum states in optical lattice using Raman transitions

• Accomplished, although we realized we could prepare a wide variety of states using lattice potentials themselves, and chose to pursue that avenue rather than Raman.

Year 2: Develop apparatus and techniques for quantum process tomography on one- and two-photon polarisation states, from full and partial data

• Accomplished complete two-photon QPT.

• Discovered surprising efficiency of adaptive tomography using partial data, but more work (both theoretical & experimental) needs to be done to determine the optimal protocol and its efficiency.

Year 3: Superoperator recovery for many-qubit photon states

• The development of the theory of postelective quantum information processing led us to shift this approach from using multiple degrees of freedom to entangling multiple photons. We thus created the first maximally-path-entangled three-photon state in year 3, and followed it up in year 4 with theoretical and experimental work on the new issues raised for tomography of such states. In year 4, we demonstrated tomography of a two-photon state using our new formalism, and now (in year 5) we are carrying out this tomography on the three-photon state.

Year 4/5: TQEC for correlated photons

• We determined the correction necessary to fix the Bell-state filter typically constructed by using an optical beam splitter.

• We used a decoherence-free-subspace encoding to reduce the sensitivity of an optical Deutsch-Jozsa algorithm to thermal noise

• We studied a variety of approaches for automated searches for decoherence-free subspaces in a two-photon system with an error model not known to the search algorithm, and discovered that a DFS could be identified much more rapidly than by extracting the complete superoperator.

Year 5: Quantum process tomography on atoms

• This project initially proceeded ahead of schedule, with QPT achieved in year 3. However, errors on the order of 5-10% proved common, and much work was required through year 4 to understand the sources of these errors and resolve them. The larger-than-expected degree of inhomogeneous broadening also required us to spend a fair amount of time on technical modifications. Now, in year 5, we have built a 3-dimensional lattice to remove the effects of transverse motion, and are about to use this, in conjunction with recently developed multiple-pulse sequences, to complete our characterisation of the multiple sources of decoherence.

Year 5: Dynamical decoupling experiment

• We have implemented a degree of DD on the optical-lattice system, and are continuing to optimize this given the real constraints on individual pulse accuracy.

Accomplishments – Theoretical side

- Reducing design constraints for spin-based quantum computer architectures.
  - Showed how to overcome the need for single-qubit control by use of two-qubit encoding, for all types of exchange interactions.
  - Showed how to construct a universal gate set from Zeeman and anisotropic exchange only.
  - Constructed a universal gate set from exchange interactions and measurements of one and two-qubit observables.
  - Designed one-spin quantum logic gates from exchange interactions and a global magnetic field.
  - Showed how to apply magnetic fields localized on single quantum dots.
- Reducing design constraints for superconducting qubits.
  - Showed how to use encoding to construct a universal gate set without the need to apply a local bias magnetic field.
- Creating decoherence-free subspaces.
  - Showed how to create collective decoherence conditions from arbitrary linear system bath interactions, using DD pulses constructed only from available physical interactions, in particular using only exchange interactions.
- Eliminating leakage.
  - Showed how to perform efficient and universal leakage elimination on physical or encoded qubits, using only the available physical interactions.
  - Designed a fault tolerant QECC protocol for universal QC using only the exchange interaction. Key ingredient: an exchange-only leakage elimination circuit.
- Hybrid error correction and prevention schemes.
  - Showed how to combine DFS and QECC to overcome spontaneous emission and collective dephasing, while performing universal QC.
  - Gave an optimal QECC for correcting spontaneous emission by combining with DD.
  - Designed hybrid DFS/QECC/DD encodings and procedures allowing for universal QC with the same resources. Showed how to implement these procedures in spin-based solid state QC and trapped-ion QC.
- Quantum dynamical decoupling.
  - Devised an algorithm for empirical determination of optimal DD pulse sequences for a given experimental system.
  - Were the first to show that DD is particularly useful for 1/f noise.
  - Designed a fault tolerant DD protocol based on concatenated pulse sequences.
  - Studied the limits of DD in light of the Zeno and anti-Zeno effect.
- Quantum process tomography.
  - Devised an optimal protocol giving a quadratic speedup over all previously known such protocols.
- Developed the first completely positive non-Markovian master equation.

Accomplishments – Experimental side

- Two-photon quantum process tomography demonstrated and applied.
    - Direct measurement of state purity demonstrated.
    - Equivalence of different bath models under QPT demonstrated
    - Investigation begun of adaptive tomography, yielding preliminary results showing a clear speed-up over the standard approach.
- Three-photon entangled states generated in a scalable arrangement.
    - Phase super-resolution demonstrated
    - New theoretical framework developed for tomography of single-mode, multi-particle states with inaccessible degrees of freedom.
- Linear-optical interferometer for arbitrary two-qubit logic
    - Demonstrated usefulness of DFS approach for reducing noise sensitivity in interferometric QC (Deutsch-Jozsa algorithm).
    - Demonstrated superiority of POVMs for optimal non-orthogonal state discrimination
- Quantum state preparation in optical lattices
    - Developed technique to filter ground vibrational state in lattice
    - Generated a variety of pure and mixed states, including a significant population inversion
    - Developed QST procedures to completely characterize the state preparation, extracting density matrices and Wigner functions (whose negativity proved the nonclassicality of the preparation)
    - Observed fractional revivals in an atom-optics delta-kicked rotor, an effect previously unobserved due to lack of long-range coherence; demonstrate utility of DKR as probe of quantum state
- Quantum process tomography in optical lattices
    - Developed automated system for extracting superoperators to characterize evolution of atomic vibration in optical lattice
    - Measured decoherence of atomic motion due to tunneling, transverse motion, and inhomogeneous broadening.
- Dynamical decoupling in optical lattice
    - Observed & optimized pulse echo in optical lattice
    - Used resulting echo to measure T2 coherence time
    - Demonstrated superiority of compound pulses over simple ones, for reducing leakage error while optimizing coherence retention
    - Characterized echo pulses using superoperator techniques
    - Demonstrated that multiple-pulse dynamical decoupling may be optimized in the presence of multiple sources of decoherence and imperfect individual pulses.
- Quantum computing in NMR

Demonstrated usefulness of DFS approach for overcoming decoherence in Grover algorithm implementation.

Lessons learned – theoretical

The focus on tailored, rather than generic error correction and prevention schemes, proved to be a very useful and powerful paradigm. Real progress was made in bringing such schemes closer to experimental realization. We found protocols that should work particularly well with spin based quantum computing architectures (in particular quantum dots) and with trapped ions. Particularly powerful was the concepts of designing error correction and prevention procedures "from the Hamiltonian up", rather than starting from a generic error model formulated in terms of Kraus operators.

The same comments apply to the approach we pursued for simplification of design constraints in quantum computing architectures. We developed a wide range of schemes allowing solid state quantum computing using only the "naturally available interactions and resources", in particular exchange interactions and global magnetic fields. This approach brought QC closer to reality, and was a useful alternative to the alternative approach of optimizing gate sequences.

The goal of designing a fully optimized QECC scheme was perhaps too ambitious when taken from the "Hamiltonian up" approach. Other groups were able to devise "generic" optimal QECC approaches based on simple error models, during the grant period. Perhaps the goal of completely general optimization along with respect for realistic design constraints was unattainable given our present tools.

Our Hamiltonian-based approach to decoherence management and simplification of design constraints was adopted by many other groups. Most recently, important results on fault-tolerant QECC for non-Markovian baths were obtained using a Hamiltonian-up style approach.The value of bringing decoherence control closer to physics is perhaps the most valuable lesson we learned, and promoted. Continuing along these lines we plan to bring to bear in the future the tools of many-body physics on realistic quantum computing scenarios involving many-particle entangled states.

In hindsight our milestones were reasonably well aligned with the order of our accomplishments. Some tasks were completed ahead of schedule, some behind, with the bulk (tailored error correction/avoidance itself) on schedule.

Lessons learned – experimental

The degree of inhomogenous broadening in non-collinear optical lattices is higher than we had expected, even when great care is taken to eliminate it. The coherence at long times is quadratically sensitive to even smooth variations in the lattice envelope, meaning that gaining more than one order of magnitude by brute force is unlikely. Transverse motion suffices to negate the effects of pulse echo over such long times. Therefore, 3D confinement is essential. While concatenated echo pulses may be useful for correcting errors, and compound pulses may reduce the pulse errors themselves, the importance of these inhomogeneous effects implies that large numbers of pulses will be needed, and for this reason, precise Raman coupling may prove more extendable than the spatial manipulation we have studied so far. On the other hand, purely spatial manipulation of the lattice has proved surprisingly versatile, and appears to allow for some coherent control, reducing leakage from the computational basis. Given our new understanding of these effects, we would have begun theoretical modeling of this process earlier, in order to develop and test new pulse sequences in the lab.

Quantum process tomography on photon pairs can be efficiently automated, and provides a great deal of useful information. Scaling to 3 or perhaps 4 photons is possible, but rates make extension much further extremely resource-intensive. Direct measurement of certain quantities, such as state purity, is possible, but typical experimental approaches to generating mixed states may not be compatible with these methods; care must be taken to clearly define the "bath" for each of the particles in the ensemble, and residual entanglement between the systems is often a problem. For certain problems, such as identifying one of a class of 2-D decoherence-free subspaces embedded in a larger space, both simulations and experiment show that a sort of adaptive tomography may be far more efficient than full process tomography. However, the optimal efficiency is not yet known, and in fact the simulations outperform our analytic theory. Again, had we been aware of the complexity which was to arise from this study, we would have devoted more time to the theoretical question early on.

When multiple photons are combined into a single-mode fiber, for instance to generate qtrits or q-quarts of polarization, or the polarization analog of path-entangled states for super-resolution, a fundamental problem arises when one wishes to perform tomography. The photons are combined so as to be experimentally indistinguishable in all respects save polarization. In practice, this indistinguishability can never be perfect, but it can be made good enough in any given experiment that the experimenters are unable to access the distinguishing degrees of freedom. In this case, it is impossible to extract the full density matrix for the (in-principle distinguishable) particles, while the standard approach of extracting a (smaller) density matrix under the *assumption* of indistinguishability has been shown to lead to incorrect results. We invented a protocol which gives the correct complete description of all measurements possible with a given setup, and demonstrated it on two photons.

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List of Publications Arising From Theoretical Portion (Lidar group)

Papers in Peer-Reviewed Scientific Journals

41. R. Woodworth, A. Mizel, and D.A. Lidar, "Few-Body Spin Couplings and Their Implications for Universal Quantum Computation", special issue on quantum computing in solid state, *J. Phys.: Cond. Mat.* **18**, S721-S744 (2006).
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